Long Beach's dual-stage NF beats single-stage SWRO

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The Long Beach Water Department (LBWD), like many Southern California utilities, has been facing the issue of decreased potable water supplies. Because of its location, the City of Long Beach is ideally situated to take advantage of desalinated seawater as a source of drinking water.

However, the primary barrier to seawater desalination has been its relatively high cost as compared to other available water sources. One method of reducing the operational cost for seawater desalination being proposed by LBWD is through a dual-staged nanofiltration (NF) membrane process, which has the potential of lowering the overall energy required.

In this configuration, permeate from the first stage is treated by the second-stage membranes to produce potable water. This article presents the data derived from the initial pilot-scale tests conducted by LBWD.

Background

Located within the coastal plain of Southern California, the City of Long Beach (City) serves approximately 70,000 acre-ft (1 acre-foot (AF) = 1234 m^3) of water to a population of 460,000. Approximately 50% of the water supply is derived from local groundwater and the balance is from imported water sources.

The imported surface water is transported from two main sources: the Colorado River and California Aqueduct. Both sources could be potentially diminished in the future due to external pressures. Under federal directives, Southern California has committed to reducing Colorado River water usage, while the reliability of the State Project water is also questionable due to many issues, including environmental concerns.

The City has been promoting the development of alternative water sources to reduce its reliance on limited imported water supplies, including seawater desalination. Desalinated seawater has been traditionally considered the last financially-feasible option, primarily due to the high treatment cost.

However, in recent years two developments have made the consideration of this option more viable, including increasing demands on available water sources, and rapid developments in membrane technology that serves to reduce costs. Several large-scale seawater desalination plants are currently in the planning or construction stages in the United States.

The current cost of surface water provided by the Metropolitan Water District (MWD) of Southern California to member utilities is $431/AF, with an increase expected in the near future. Although the cost of desalinating seawater may be substantially higher, MWD has been actively encouraging the development of alternative supplies of drinking water, including seawater desalination. As an incentive, MWD is offering a subsidy of up to $250/AF to promote seawater desalination within its service area, making seawater desalination a more economically feasible alternative.

A major contributor to the cost of seawater membrane desalination is energy consumption. In past years, research trends have focused on increased membrane productivity and system recovery in order to minimize footprint and system capital cost. High productivity and system recovery is typically achieved by increasing the overall system pressure. Thus, vendors have introduced membranes and vessels that are capable of withstanding pressures that are greater than 1,000 lb/in^2 (psi), allowing higher membrane flux and overall system recovery.

One concept that has not been examined extensively is the use of lower-pressure desalting membranes (e.g. nanofiltration) for seawater desalination. This concept is particularly attractive in areas where energy costs are high, such as California. This paper presents an innovative approach to seawater desalination, developed by the City, using a patent pending dual-staged NF process for the production of drinking water.

Study Objectives

The objective of this study is to determine whether the dual-staged NF membrane process is capable of producing water of potable quality.

Literature Review

NF was primarily developed as a membrane-softening process, offering an alternative to chemical softening [1]. NF is also effective in the removal of disinfection byproduct (DBP) precursors [2-4] and International Desalination Association BAH03-173 [3] other synthetic organic chemicals (SOCs) [5]. There are currently several full-scale NF plants worldwide that target the removal of hardness and/or DBP precursor removal from surface or groundwater supplies.

Recently, the Saline Water Conversion Corporation in Saudi Arabia (SWCC, Saudi Arabia) evaluated the effectiveness of NF as a pretreatment to seawater reverse osmosis (SWRO) membranes [6-9]. The main objectives for the NF pretreatment of SWRO feed were to:

a) minimize particulate and microbial fouling of the SWRO membranes by removal of turbidity and bacteria;
b) prevent scaling by removal of the hardness ions; and
c) lower the operational pressure of SWRO process by reducing the feedwater's total dissolved solids (TDS) concentration.

Several publications presented by SWCC addressed various issues related to the application of NF pretreatment for SWRO. Early work was performed at a pilot facility [6-8] in which Persian Gulf seawater (TDS = 44,000 mg/L) was first pretreated through multimedia filters, cartridge filter, and NF membranes. The NF permeate was subsequently treated through the SWRO process, which produced potable water. The concentrate was further processed through a multistage flash (MSF) distillation unit.

Various unspecified NF and SWRO membrane types were evaluated in the study.

Subsequently, SWCC converted one of

two SWRO parallel trains (Umm Lujj SWRO plant, Saudi Arabia) from a single SWRO into a NF-SWRO train to evaluate the NF pretreatment[9].

The second identical train was maintained as a single SWRO process to serve as the reference process, with each train having a capacity of 0.6 MGD. For the demonstration plant, the NF-SWRO train showed an increase in productivity of 42% and an increase in system recovery from 28 to 56%, compared with the single SWRO train. Additionally, the energy consumption of the NF-SWRO train was 23% lower than the single SWRO train.

Although NF membranes have been previously tested with seawater, the application focused on using NF as pretreatment for the reverse osmosis membrane stage rather than using these membranes to produce potable water. In recent years, however, significant developments of NF membranes have been made, resulting in products that can achieve high TDS rejections (> 90%) at lower applied pressures. These advances allow a two-step, permeate-staged NF treatment process capable of producing potable water with lower overall applied pressure, and subsequently, lower operational costs, conceptually feasible.

To date, this concept does not appear to have been tested, as evidenced by the lack of literature in this area.

Materials And Methods

As a first step, attempts were made to model the performance of NF membranes through commercially available membrane performance projection software programs (eg, ROPro®). However, these attempts were unsuccessful due to the inability of these programs to converge on a solution. Actual testing was deemed necessary to determine the performance of NF membranes for seawater desalination.

A single five-element vessel (4") membrane skid was initially used to test various NF membrane types. These included products from Dow/FilmTec, Koch/Fluid Systems and Osmonics-Desal, and will be designated as Membranes A, B, C, D (in no specific order). The NF membranes selected were based of the manufacturers' claims of high salt rejection (eg, magnesium sulfate rejection > 95%).

The pilot system was operated on a closed-loop basis, with the brine and permeate recirculated back to the feedwater supply tank. Closed-loop operation was necessary given the lack of a readily available seawater supply at the site of the pilot testing. Approximately 2,000 gallons (7500 litres) of Pacific Ocean seawater was used during the tests in a recycle mode.

Although Pacific Ocean seawater salinity level is typically reported in the literature as less than 35,000 mg/L, salinity levels of the recycled feed water reached as high as 37,500 mg/L during a few tests. This was due to the fact that not all of the permeate was recycled during a part of the testing.

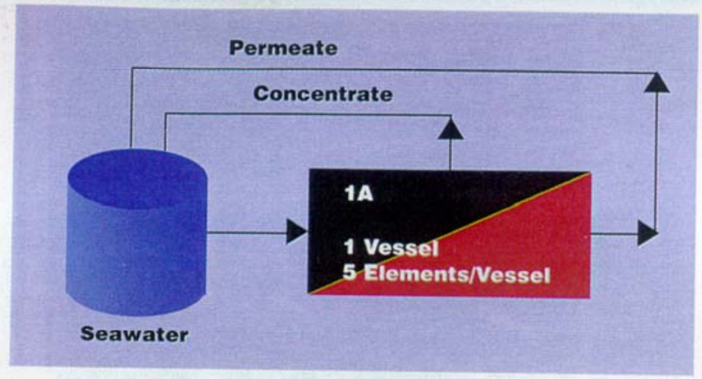

Figure 1a: Schematic of Phase I Test Setup

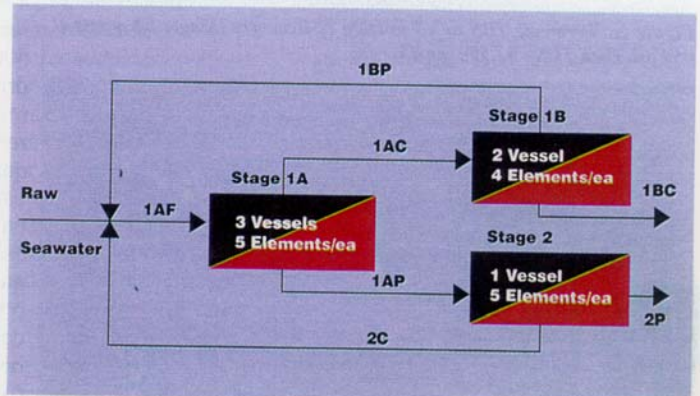

Figure 1b: Schematic of Phase II Test Setup

This artificially concentrated saline water was later discharged, and refilled with fresh seawater. All of the permeate and the brine flows were subsequently recycled during later testing.

The recirculating test unit was allowed to operate for at least 75 minutes prior to sample collection, based on the calculated detention time in the system. All water quality analyses were conducted in accordance with Standard Methods [10]. Initial single-element tests identified the rejection capabilities of each membrane tested and the data were used to select one membrane type for subsequent testing.

Figure 1a shows the schematic for the single vessel skid. Pretreatment provided in this configuration and the subsequently modified membrane skid consisted of only 5-µm cartridge filtration. No antiscalant or other chemicals were added during these tests.

Modifications to the single five-element vessel (4") membrane skid were then made to accommodate the next phase of testing. This included the addition of a second stage, five-element vessel to treat the first stage permeate.

Figure 1b shows the schematic for the modified skid, which includes three five-element vessels for the first stage in order to allow enough permeate flow to feed the single vessel for the second stage. Two four-element vessels were also added to further treat the first-stage brine and improve overall product recovery

Results and Discussion

Initial single-element membrane screen testing was performed at a range of applied pressure of 375 to 525 psi. Figures 2a and 2b present the variation of permeate TDS and flux, respectively, as a function of system recovery under an applied pressure test of 450 psi.

Although only test results performed at 450 psi are shown here, tests results obtained at the other pressures yielded similar trends. The data clearly show that Membrane A is a much tighter membrane, resulting in lower product water TDS and flux compared with the other membranes.

Figure 3 presents the variation of TDS rejection of Membrane A as a function of membrane flux and applied pressure.

Membrane A was considered the best performing for this application because it was the only one capable of achieving greater that 90% TDS rejection within the applied pressure tested (400 to 500 psi), yielding a flux range of 6 to 12 gallons per ft^2 per day (gfd). Achieving the higher TDS rejections in the first stage NF process is necessary to produce potable water quality by the dual-staged NF process. Hence, Membrane A was selected for the subsequent testing phase.

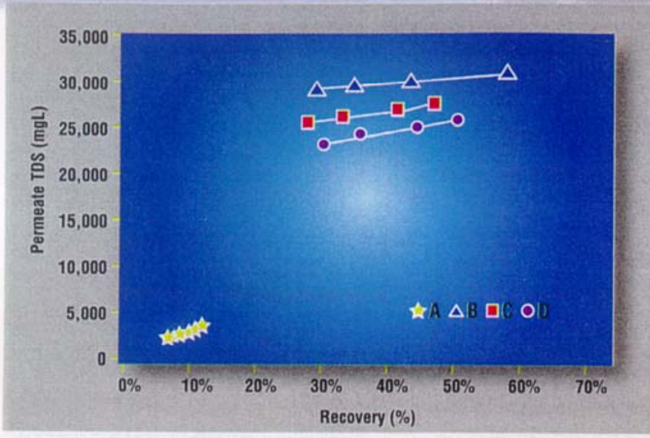

Figure 2a: Permeate TDS as a Function of Recovery (Single Elements at 450 psi, Feed TDS= 33,500 mg/L)

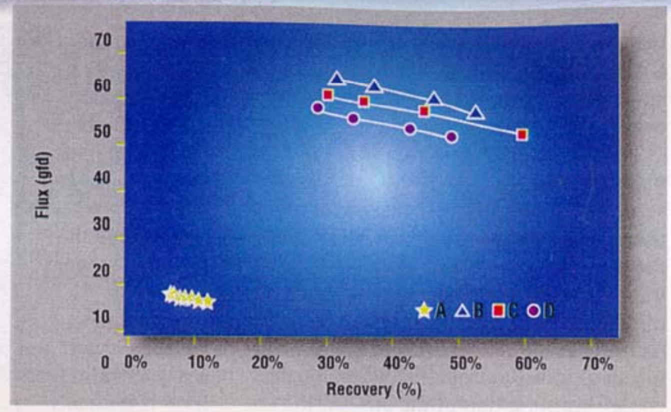

Figure 2b: Flux as a Function of Recovery (Single Element at 450 psi)

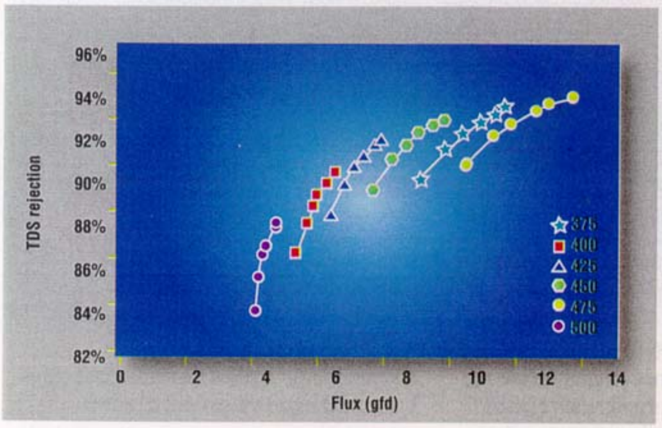

Figure 3: TDS Rejection as a Function of Flux and Applied Pressure (Membrane A)

Dual-staged NF system

The second phase of testing used the dual-staged NF system as shown in Figure 1b. Tables 1 and 2 provide representative operational and water quality parameters of the treatment process collected in a single treatment run.

	Unit	Stage-1	Stage-2
Temperature	°C	26	–
Flux	gfd	8.4	18
Flux (20°C)	gfd	7.4	16
Applied Pressure	psi	560	230
Recovery	%	40%	73%

Table 1: Operating Parameters During Phase II Testing

The first stage operated at an overall recovery of approximately 40% and an applied pressure of 560 psi. The second-stage NF membrane operated at a greater recovery of 73% and a lower applied pressure of 230 psi. Overall, the system recovery was 37%, recognizing that the second stage reject has a lower salinity than the feedwater and is recycled to the first stage feed.

The TDS of the second-stage NF permeate was 250 mg/L, well within the secondary MCL of 500 mg/L for drinking water. For reference, representative water quality within the City is also shown on this table.

The mineral quality of the NF product was comparable or better than the City's water. As expected, the desalinated seawater is more corrosive than the drinking water, as measured by the Langelier Saturation Index (LSI), and is comparable to the TDS of waters produced by conventional RO treatment. The above operational and water quality data were reproducible, with minor variations, in several batch treatment tests.

Process Advantages

There are several potential advantages from the dual-staged NF system, including system flexibility. The option for operating the two passes independently (different recoveries, pressures, types of membranes (salt rejections), and recycle flows) provides greater flexibility that results in many of the potential benefits identified in this section as described below.

Source Water and Pretreatment

Many seawater sources experience variations in salinity, caused by seasonal, tidal, or following storm events. The San Francisco Bay in the vicinity of Marin County (a seawater desalination site) experiences TDS as low as 20,000 mg/L due to fresh water runoff during the rainy season, in contrast to the 35,000 mg/L TDS that is normally associated with Pacific Ocean seawater. The system flexibility of the dual-staged NF process has shown the potential for being able to adjust to the wide variations in feedwater salinity.

Other variations in source water quality, including temperature, can also be readily managed in the two-pass LBWD system. Temperature impacts are much less than those of salinity variations, but must still be considered.

Membrane System

The membranes for the second permeate stage are exposed only to feedwater of higher quality (first-stage permeate). As a result, the designers have several potential cost-saving options, including high flux rate (>16 to 25 gfd), increasing membrane surface area per element, and even using hollow fibre configuration elements. Using conventional spiral elements, the greater hydraulic flow to individual vessels (high flux or greater membrane area) could reduce the number of elements and vessels required.

The performance of membranes deteriorates over time as irreversible fouling occurs, interfering with the hydraulic and salt rejection properties. Designers typically adopt 3-6 year membrane lives for economic evaluations. A two-stage system provides the potential for longer useful membrane lives as product water quality requirements can be met through the great flexibility of the system. A 30-50% increase in membrane life may reduce the overall water production costs by 5-15%.

The lower operating pressures of the system relative to conventional SWRO (900 to 1,000 psi) provide an opportunity to use less costly materials. The second stage, operating at pressures less than 350 psi, could make extensive use of non-ferrous material and eliminate the corrosion potential. The lower pressures of the dual-staged NF system (relative to single stage SWRO) can result in use of

Consituent	Unit	Raw Seawater	Stage 1A Permeate	Stage 1A Permeate	LBWD Tap
mg^{2+}	mg/L	1532	28	0.2	13
Ca^{2+}	mg/L	546	10.1	0.1	39
SO_4^{2-}	mg/L	2888	33	0.2	100
Na^4	mg/L	11912	1280	92	75
C^1	mg/L	19737	1806	117	59
TDS	mg/L	37480	3247	218	390
Hardness (as$CaCO_3$)	mg/L	7755	140	1.26	151
pH	_	8.01	7.84	7.37	8.16
LSI	_	1.12	-1.93	-4.56	0.34

Table 2: Selected Water Quality Parameters During Phase II Testing

lower pressure rated pumps, resulting in lower-cost pumping systems.

The use of two passes of lower salt rejection membranes instead of the high salt rejection single-stage SWRO membranes allows a wider range of membranes to be considered. The increased competition between membrane manufactures should result in lower membrane costs.

Product Water Quality

The dual-staged seawater NF system can produce better quality water than a conventional single-stage SWRO. Historically, conventional SWRO systems can only achieve TDS levels consistently below 250 mg/L through a partial second stage.

The dual-staged NF system has the ability to produce permeate over a wide quality range. This is advantageous in water systems where SWRO permeate is blended with other potable supplies which vary seasonally in quality and quantity. For example, the mix of groundwater to surface water varies seasonally in the City of Long Beach, as does the mix of surface waters. Flexibility is an advantage if the permeate is to be used for multiple applications having differing quality requirements.

Because the permeate from the first stage is treated through the second stage, the dual-staged NF system inherently provides two "barriers", and may receive consideration from regulatory agency for higher disinfection credits than a single-stage conventional SWRO system. This would reduce the post-treatment disinfection requirements.

Conclusions

The data presented above show that the dual-staged NF membrane process is capable of producing potable water from Pacific Ocean seawater. The TDS of the product water was lower than 500 mg/L and the applied pressures were less than 550 psi in the first stage and 250 psi in the second stage. Hence, the process clearly has potential to reduce the energy requirements for seawater desalination.

Several advantages of the dual-staged NF system were also introduced in this paper. Further work is necessary to optimize the dual-staged NF process application for seawater desalting in order to fully capitalize on the advantages presented.

Future Work

Based on the above results, a patent was registered on the two-step, permeate-staged NF process for seawater desalination by the City of Long Beach. Plans for further work include the construction of a 300,000 gpd demonstration facility to test the pretreatment and post treatment processes. This facility is expected to be completed by the first part of 2004 and will also provide information on long-term membrane performance as well as energy-recovery.

More detailed cost information will be developed during this time that should address the feasibility of the construction of a full-scale (up to 10 million gallons per day (mgd)) desalination facility for the City. Further investigations into the pretreatment, as well as posttreatment issues, including water blending, will also be conducted.

Acknowledgements

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Biographies

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